Fatigue-Fractured Surfaces and Crack Paths of Textured Polycrystalline Magnesium Alloys

S. Morita[1], K. Matsushita[1], T. Mayama[2], T. Hirai[3], T. Enjoji[4] and N. Hattori[1]

[1] Department of Mechanical Engineering, Saga University, Saga 840-8502, Japan, morita@me.saga-u.ac.jp
[2] Priority Organization for Innovation and Excellence, Kumamoto University, Kumamoto 860-8555, Japan, mayama@kumamoto-u.ac.jp
[3] Material and Environment Department, Industrial Technology Center of Saga, Saga 849-0932, Japan, hirai@saga-itc.go.jp
[4] Material and Environment Department, Industrial Technology Center of Saga, Saga 849-0932, Japan, enjoji@saga-itc.go.jp

ABSTRACT. *The influence of texture on fatigue crack propagation behavior of rolled AZ31B magnesium alloy was investigated. Fatigue crack propagation tests were performed on compact tension (CT) specimens at a stress ratio of R=0.1 and a frequency of 10 Hz at room temperature in air. Three types of specimens were machined from rolled plate; fatigue cracks propagated parallel to the transverse direction (L-T and S-T specimens) and parallel to the short transverse direction (L-S specimen). The crack growth rate (da/dN) of the L-T and S-T specimens showed similar behavior in the examined stress intensity factor (ΔK) range. Fracture surfaces of the L-T and L-S specimens showed many steps parallel and perpendicular, respectively, to the macroscopic crack growth direction. On the other hand, fracture surfaces of the S-T specimen showed various directional steps independent of macroscopic crack growth direction. Free deformation twins were observed around the fatigue crack path in the L-T, L-S and S-T specimens.*

INTRODUCTION

Magnesium alloys are the lightest structural material with a relatively high strength-to-weight ratio and stiffness. These features make magnesium alloys attractive for applications in the automotive and aircraft industry [1]. Wrought Mg-Al-Zn system alloys, rolled and extruded magnesium alloys, are suitable candidates for structural parts. It is important to elucidate the cyclic loading behavior and fatigue properties of the material used for structural parts.

It is well known that wrought magnesium alloys have a hexagonal close-packed (HCP) structure, and strong textures are formed by rolling and extrusion. In polycrystalline magnesium alloys, basal planes are aligned parallel to the rolling direction by rolling. On the other hand, basal planes are distributed parallel to the extrusion direction by extrusion. Depending on their texture, wrought magnesium alloys show unique deformation behavior such as mechanical anisotropy [2-4], pseudoelasticity in compression and tension loading-unloading [4-8], and asymmetricity of stress-strain hysteresis loops in strain controlled low-cycle fatigue tests [9-14] and even in load controlled high-cycle fatigue tests [3, 9], etc. The orientation dependence of fatigue crack propagation behavior of magnesium single crystals [15-17], and the effect of grain size [18-21] and texture [22-26] on fatigue properties of polycrystalline magnesium alloys have been reported in previous works. However, the effect of texture on the fatigue crack propagation behavior of textured polycrystalline magnesium alloys is still poorly understood. In the present study, the effect of texture on the fatigue crack propagation behavior of rolled AZ31B magnesium alloy is investigated.

EXPERIMENTAL PROCEDURES

Material and Test Specimen

Commercial rolled AZ31B magnesium alloy plate (16 mm thickness) was used in the present study. Chemical composition of the alloy is shown in Table 1. The alloy has equiaxed grains, and the average grain size was approximately 20 μm. The alloy showed typical texture as shown in Fig.1; basal planes were aligned parallel to the rolling direction. Monotonic compressive and tensile mechanical properties of the alloy are summarized in Table 2. It is emphasized that the ratio of compressive/tensile 0.2% proof stress of the alloy is approximately 0.52.

Table 1. Chemical composition (mass%)

Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
3.13	0.98	0.29	0.01	0.005	0.004	0.002	Bal.

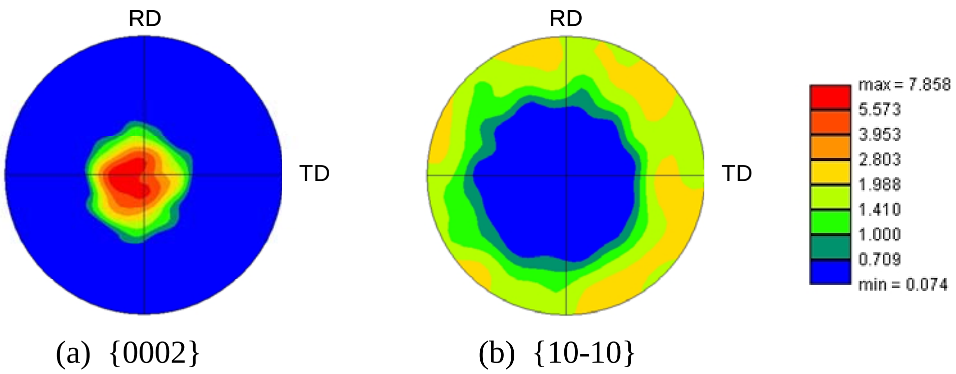


Figure 1. {0002} and {10-10} pole figures of rolled AZ31B magnesium alloy.

Table 2. Monotonic mechanical properties

Material	Compressive 0.2% proof stress $\sigma_{0.2comp}$ (MPa)	Tensile 0.2% proof stress $\sigma_{0.2tens}$ (MPa)	Ultimate tensile strength σ_B (MPa)
Rolled AZ31	75	145	253

Compact tension (CT) specimens with a width (W) of 12 mm, a thickness (B) of 6 mm, an initial crack length (a) of 4 mm were machined from a rolled plate as shown in Fig.2. Loading axes were parallel to the rolling direction; fatigue crack propagated parallel to the transverse direction (L-T specimen) and parallel to the short transverse direction (L-S specimen). In addition, loading axis was perpendicular to the rolling direction; fatigue crack propagated parallel to the transverse direction (S-T specimen).

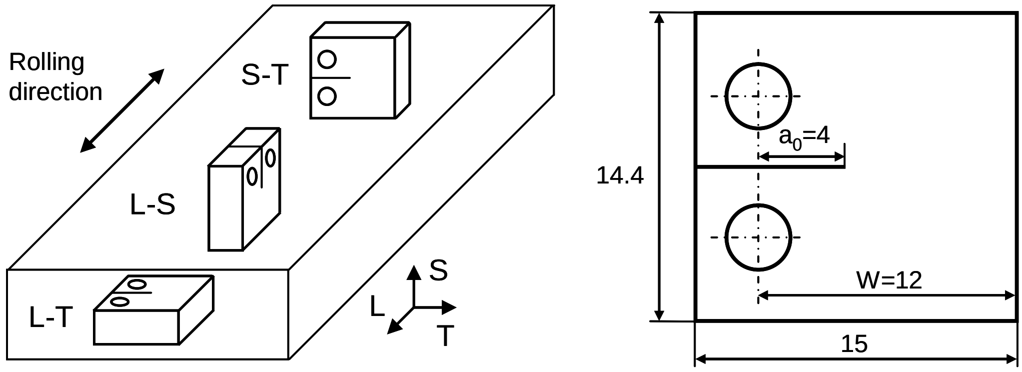


Figure 2. Shape and dimensions of CT specimen (in mm).

Fatigue Crack Propagation Test

Fatigue crack propagation tests were performed on an electro-hydraulic testing machine (capacity: 9.8 kN) at a stress ratio of $R = P_{mim}/P_{max} = 0.1$ (tension-tension) and a frequency of 10 Hz at room temperature in air. Here, P_{min} and P_{max} are the minimum and maximum applied load, respectively. The fatigue crack length was determined using a microscope. The stress intensity factor (ΔK) range was calculated using the following equation:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \cdot \frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4\right] \quad (1)$$

where P is the applied load, and W, B and a are the width, thickness, and crack length, respectively.

The fracture surface of the fatigue tested specimens were observed by SEM.

RESULTS AND DISCUSSION

The relationship between the crack growth rate (*da/dN*) and the ΔK range is shown in Fig.3. The figure shows that the fatigue crack propagation behavior of the L-T and S-T specimens is similar in the examined ΔK range. On the other hand, the fatigue crack propagated up to several hundred micrometers in the L-S specimen.

The reverse plastic zone size (r_c) under plane strain condition is defined as [18]

$$r_c = \left(\frac{1}{10\pi}\right)\left(\frac{\Delta K}{\sigma_{ys}}\right)^2 \tag{2}$$

where σ_{ys} is tensile yield strength (The value of the rolled alloy was 145 MPa). In the examined ΔK range, the minimum length of the reverse crack tip plastic zone of the L-T and L-S specimens were estimated to be approximately 25 μm. The minimum length of

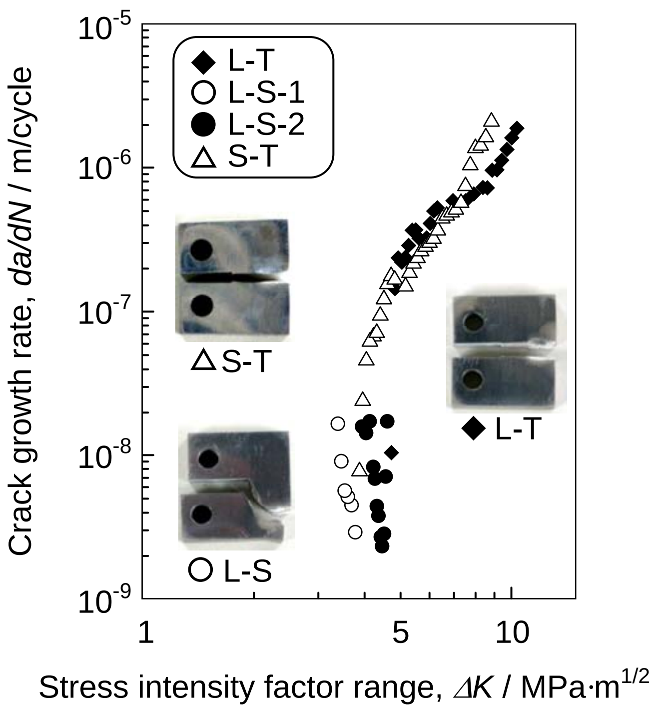
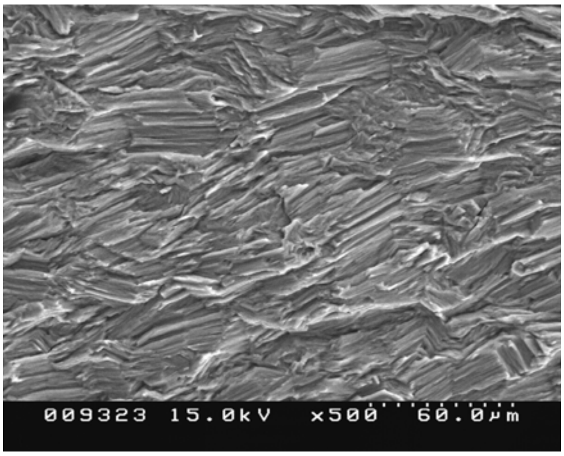


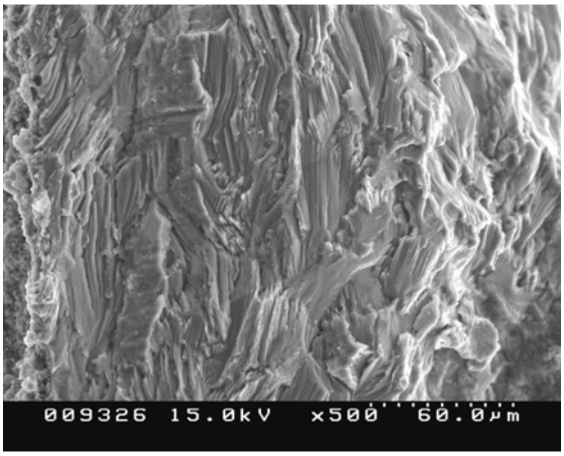
Figure 3. Relationships between crack growth rate and stress intensity factor range.

the reverse crack tip plastic zone is comparable to the grain size (20 μm) for the L-T and L-S specimens. As ΔK is increase up to stable growth ΔK (ΔK = 5 MPa·m$^{1/2}$), the minimum length of the reverse crack tip plastic zone becomes larger than the grain size.

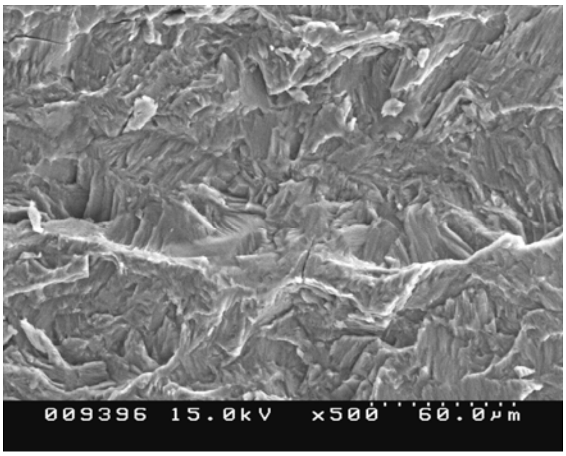
Figure 4 shows the typical SEM images of the fatigue tested L-T, L-S, and S-T specimens. Many straight lines or steps were observed over several grains along with the macroscopic direction of fatigue crack growth in the L-T specimen (Fig.4(a)). In contrast, in the L-S specimen, many lines or steps perpendicular to the macroscopic direction of fatigue crack growth were observed (Fig.4(b)). On the other hand, various directional steps independent of the macroscopic direction of fatigue crack growth were observed in the S-T specimen (Fig.4(c)). The fracture surface of the L-T, L-S and S-T specimens had a similar morphology and did not depend on ΔK.



(a) L-T specimen



(b) L-S specimen

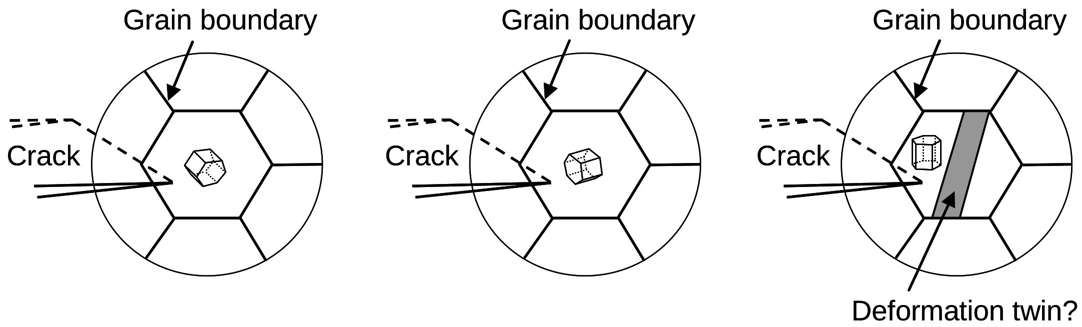


(c) S-T specimen

Figure 4. Fracture surfaces.

Morita et al. [26] reported that the effect of texture on fatigue crack propagation behavior of rolled and extruded AZ31 magnesium alloys. They found that the *c*-axis direction is unfavorable for the fatigue crack propagation in textured polycrystalline magnesium alloys. In other words, the *a*-axis direction is favorable for fatigue crack propagation. Moreover, straight lines or steps parallel to the direction of fatigue crack growth were observed when the fatigue crack propagated parallel to the *a*-axis in rolled AZ31 magnesium alloy. The relationship between the macroscopic direction of the fatigue crack growth and the crystallographic orientation of each grain in rolled AZ31B magnesium alloy is shown in Fig. 5.

In addition, the deformation twinning of polycrystalline magnesium alloys plays an important role in the deformation process because of the limitation of slip system. When the specimens were subjected to a stress higher than the compressive and tensile yield stress in the load-controlled fatigue test, deformation twins were observed in the extruded magnesium alloys [3, 4, 27]. In contrast, free deformation twins are observed around the fatigue crack path (within the plastic zone) in the L-T, L-S, and S-T specimens. It appears that the fatigue crack growth is not controlled by the deformation twinning at a crack tip in textured polycrystalline magnesium alloys.



(a) L-T specimen (b) L-S specimen (c) S-T specimen

Figure 5. Schematic illustrations of a crack tip.

SUMARRY

The fatigue crack propagation behaviors of three types of specimens of textured polycrystalline magnesium alloys, in which the macroscopic fatigue crack propagated perpendicular to and parallel to the basal plane of each grain, has been investigated. It is found that the fracture surfaces depend on the initial crack plane and the macroscopic fatigue crack propagation direction in textured polycrystalline magnesium alloy.

ACHNOWLEDGMENTS

This work was supported by Saga University Dean's Grant 2011 For Promising Young Researchers.

REFERENCES

1. Ebert, T., Mordike, B.L. (2001) *Mater. Sci. Eng. A* **302**, 37-45.
2. Yukutake, E., Kaneko, J. and Sugamata, M. (2003) *Mater. Trans.* **44**, 452-457.
3. Somekawa, H., Maruyama, N., Hiromoto, S., Yamamoto, A. and Mukai, T. (2008) *Mater. Tran.* **49**, 681-684.
4. Morita, S., Tanaka, S., Ohno, N., Kawakami, Y. and Enjoji, T. (2010) *Mater. Sci. Forum* **638-642**, 3056-3061.
5. Cáceres, C.H., Sumitomo, T. and Veridt, M. (2003) *Acta Mater.* **51**, 6211-6218.
6. Li, Y., Enoki, M. (2007) *Mater. Trans.* **48**, 1215-1220.
7. Li, Y., Enoki, M. (2007) *Mater. Trans.* **48**, 2343-2348.
8. Li, Y., Enoki, M. (2008) *Mater. Trans.* **49**, 1800-1805.
9. Hasegawa, S., Tuchida, Y., Yano H. and Matsui, M. (2007) *Int. J. Fatigue* **26**, 1839-1845.
10. Lin, X.Z., Chen, D.L. (2008) *Mater. Sci. Eng. A* **496**, 106-113.
11. Matsuzuki M., Horibe, S. (2009) *Mater. Sci. Eng. A* **504**, 169-174.
12. Begum, S., Chen, D.L., Xu, S. and Luo, A.A. (2009) *Mater. Sci. Eng. A* **517**, 334-343.
13. Lv, F., Yang, F., Duan, Q.Q., Luo, T.J., Yang, Y.S., Li, S.X. and Zhang, Z.F., (2009) *Scripta Mater.* **61**, 887-890.
14. Park, S.H., Hong, S.G., Bang, W. and Lee, C.S. (2010) *Mater. Sci. Eng. A* **527**, 417-423.
15. Ando, S., Iwamoto, N., Hori, T. and Tonda, H. (2001) *J. Japan Inst. Metals* **65**, 187-190.
16. Ando, S., Saruwatari, K., Hori, T. and Tonda, H. (2003) *J. Japan Inst. Metals* **67**, 247-251.
17. Ando, S., Ikejiri, Y., Iida, N., Tsushida, M. and Tonda, H. (2006) *J. Japan Inst. Metals* **70**, 634-637.
18. Kim, H.-K., Lee, Y.-I. and Chung, C.-S. (2005) *Scripta Mater.* **52**, 473-477.
19. Uematsu, Y., Tokaji, K., Kamakura, M., Uchida, K., Shibata, H. and Bekku, N. (2006) *Mater. Sci. Eng. A* **434**, 131-140.
20. Ochi, Y., Masaki, K., Hirasawa, T., Wu, X., Matsumura, T., Takigawa, Y. and Higashi, K. (2006) *Mater. Trans.* **47**, 989-994.
21. Tsushida, M., Shikada, K., kitahara, H., Ando, S. and Tonoda, H. (2008) *Mater. Trans.* **49**, 1157-1161.
22. Sajuri, Z.B., Miyashita, Y., Hosokai, Y. and Mutoh, Y. (2006) *Int. J. Mech. Sci.* **48**, 198-209.
23. Ishihara, S., Nan, Z. and Goshima, T. (2007) *Mater. Sci. Eng. A* **468-470**, 214-222.

24. Zeng, R.C., Xu, Y.B., Ke, W. and Han, E.H. (2009) *Mater. Sci. Eng. A* **509**, 1-7.

25. Zeng, R., Han, E., Ke, W., Dietzel, W., Kainer, K.U. and Atrens, A. (2010) *Int. J. Fatigue* **32**, 411-419.
26. Morita, S., Ohno, N., Tamai, F. and Kawakami, Y. (2010) *Mater. Trans.* **51**, 1543-1546.
27. Yang, F., Yin, S.M., Li, S.X. and Zhang, Z.F. (2008) *Mater. Sci. Eng. A* **491**, 131-136.